A CONVENIENT METHOD FOR REFERRING SECONDARY FREQUENCY STANDARDS TO A STANDARD TIME INTERVAL*

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Summary—A method is described for obtaining a convenient low frequency from a high-frequency standard by means of harmonic control of distorted wave oscillators (multi-vibrators). In the equipment described two such oscillators are employed, for convenience in arriving at a harmonic series of frequencies, based on 10-kc fundamental, as well as a frequency of 1 kc for operation of the clock motor, from a standard frequency of 50 kc. The conclusions based upon an experimental investigation of harmonic control of the distorted wave oscillators are given. Representative curves of the variations in frequency of the 50-kc standard for 10-day intervals are shown.

1. INTRODUCTION

IN recent years the technique of frequency standardization has been refined and improved through the development of oscillating systems which are so nearly invariant that their average frequency is practically independent of the time interval for which the average is determined. Such a system permits the determination of frequency, by counting successive cycles, to a degree of precision which is usually limited only by the patience of the observer. Extensive use of this "absolute" method of frequency measurement has suggested the concept of the earth's rotational frequency, or a time interval defined thereby, as a fundamental standard for frequencies of all magnitudes.

Practical methods for maintaining various types of oscillators as the intermediate links between the desired frequency and a standard time interval have been described in the literature. It is the purpose of the present paper to call attention to an application of the same general principle to a specific problem of laboratory calibration. The results described have a general significance insofar as they relate to the establishment of a harmonic series of standard frequencies.

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At the present time there are approximately 600 radio broadcast stations operating more or less continuously in the United States. The transmitters of these stations have an irregular geographical distribution and to each transmitter is assigned as a carrier one of the 96 decimal frequencies between and including the limits of 1500-550 kc. The universal problem of interference is not solved by accurate maintenance of the carrier frequencies on their assigned values, but such maintenance is obviously a primary essential. Although piezo-electric oscillators, or their equivalent, will ultimately be incorporated as integral frequency control elements of all broadcast transmitters, such arrangements are not now in general use. Small portable piezo oscillators are widely employed in the broadcasting stations as comparison standards, by means of which their carrier frequencies may be occasionally corrected. The problem of accurate adjustment of quantities of these control and comparison standards to the even decimal frequencies employed by these stations has suggested the calibration method which we are to describe.

2. Experimental Method

The general technique of "direct" calibration from a single-frequency source, which in turn is compared with the earth's rotational frequency, is based upon an assumption which may be stated as follows: if oscillations of constant periodicity occur in two independent systems and either system be so adjusted that the fundamental constituent of its oscillation coincides constantly with a harmonic constituent of the oscillation in the other system, then the fundamental frequency of either system is uniquely determined in terms of the other. The propriety of this assumption will not be discussed here although other investigators have given attention to specific phases of it, as for instance by examining the validity of identifying with integral harmonic ratios the various emission frequencies from a multivibrator[1]. If, therefore, our fundamental oscillation occurs at a low frequency and is associated with a substantial series of real harmonics, the physical comparison of an unknown frequency with the frequency of one of these harmonics is considered to be an absolute comparison with the fundamental. Since the ultimate standard of frequency is very low indeed compared with what

[1] D. W. Dye, "A Self-Contained Harmonic Wavemeter", *Phil. Trans. Roy. Soc.* of **224**, A, London, 279.

we normally have to measure, it is customary to employ the intermediate source of oscillations previously mentioned as the basis of the harmonic series from which calibrations are actually made.

An electro-mechanical oscillator such as a tuning fork has been extensively used as an intermediate source. A tube-driven fork can be coupled directly to the counting mechanism, but the fundamental frequency is inconveniently remote from the frequencies at which calibrations are required in the present case; also the fork is subject to the familiar limitations arising from its damping and its temperature coefficient. The use of a piezo-electric oscillator as the intermediate source has been described in an important paper read before the Washington meeting of U.R.S.I. in October, 1927.[2] The quartz oscillator exhibits small perturbations under reasonable operating conditions, and permits the establishment of a harmonic series from a fundamental of higher frequency. It requires, however, a very stable and reliable electrical system for converting its fundamental frequency into a lower frequency suitable for operating the counting mechanism.

In the system to be discussed in the present paper, a piezo-electric oscillator is employed as the intermediate source. But for the step-down frequency converter, a system describing "relaxation oscillations"[3] is adopted because it has been found to offer many advantages for the specific problem in hand. An intermediate frequency of 50 kc is chosen for convenience. The relaxation oscillator can be adjusted to yield a highly stable fundamental at 1 kc or even less, directly controlled by the 50-kc source, which operates a small impulse motor, running in air, for the counting mechanism. Furthermore, the controlled relaxation oscillator, if properly designed, is an extremely simple piece of equipment.

Two general types of relaxation oscillator have been suggested for use as step-down frequency converters. The simplest is a neon discharge tube, used in virtue of its so-called cut-off characteristic to sustain oscillations in a circuit comprising a direct-current source, a resistance, and a condenser. The oscil-

[2] J. W. Horton and W. A. Marrison, "Precision Determination of Frequency." Paper read at meeting of the International Union of Scientific Radiotelegraphy, Washington, D. C., Oct. 13, 1927. PROC. I.R.E., **16**, 137; February, 1928.

[3] Balth. van der Pol, Jr., "On Relaxation Oscillations," *Phil. Mag.*, 978, Nov., 1926, also *Zeits. f. Hochfreq. Technik*, **29**, 114, 1927.

lations of such a circuit are rich in harmonics and if a second oscillation of a higher frequency is injected into the circuit, the relaxation oscillation may assume a frequency which is an integral submultiple of the injected frequency. It is possible to maintain an oscillation in such a circuit whose fiftieth harmonic coincides with the injected frequency. But the behavior of this control effect on such high orders is relatively unsatisfactory, as minute variations in either the injected voltage or the direct voltage are likely to destroy the control. The other type of oscillator is the Abraham-Bloch multivibrator. Doubtless there are many other forms of relaxation oscillator which present similar characteristics, but the modified multivibrator has proved so satisfactory that no others have been investigated.

The multivibrator consists essentially of an aperiodic circuit in which oscillations of irregular waveform are sustained by a triode excited by a second triode which provides the proper phase relation for maintenance. It was first used as a rich source of harmonics, in which the fundamental constituent is determined by and probably maintains a constant phase relation with a low-frequency injected oscillation. In its usual form it therefore constitutes a frequency multiplier or step-up frequency converter suitable for comparing high frequencies with a low-frequency standard. Some time ago one of the present authors[4] suggested the possibility of controlling a multivibrator at a fundamental frequency which is an integral submultiple of the injected control frequency, thus making it a step-down frequency converter. In this case the control oscillation coincides with a harmonic of the multivibrator. When this condition is established experimentally, the multivibrator is definitely controlled by the injected high-frequency oscillation, and the multivibrator oscillation has certain characteristics which distinguish this "controlled" state of oscillation. Since this system appears to be well adapted for driving a counting mechanism at frequencies as low as one one-hundredth of the constant frequency source, we shall examine in detail its behavior in the role of a controlled submultiple generator.

[4] J. K. Clapp, "Universal Frequency Standardization from a Single Frequency Source," *Jour*. Opt. Soc. Amer. and Rev. Scien. Instr., **15**, 25, July, 1927.

3. Harmonic Control of Multivibrator

No adequate mathematical analysis of the action of the multivibrator has been given. In the practical case large voltage amplitudes are encountered, carrying the operating points of the vacuum tubes far beyond the region of the characteristic which might be treated under limited series solutions for small amplitude oscillations such as van der Pol's.[3] But large amplitudes are required to obtain an extended series of harmonic frequencies of useful amplitude. It thus appears that the only feasible investigation of multivibrator oscillations, meeting our physical requirements, demands sufficiently complete experimentation to permit valid generalizations to be drawn.

The basic assumption of integral ratios between the harmonics and fundamental *emitted* by a multivibrator allows frequency comparisons to be made, but does not necessarily imply that the controlled multivibrator has a harmonic frequency, of value equal to the frequency of the controlling source, and of invariant phase with respect to this source. A regular, or irregular, variation in phase might conceivably exist.

We define the "controlled" state for the multivibrator as that state of operation in which one of the multivibrator harmonics does not change phase with respect to the fundamental frequency of the controlling source by more than 360 electrical degrees in any arbitrary time interval. Then, by the assumption of integral harmonic frequencies, the fundamental frequency of the multivibrator is an exact submultiple of the controlling frequency. We shall next examine the experimental conditions for permanently establishing this controlled state on the desired harmonic order.

All the experiments have been carried out with no inductance, save that of strays, in the circuits of the multivibrators because it seemed logical to reduce the electrical inertia to a minimum when searching for the most stable and unambiguous control condition.

Preliminary studies indicated that the control stability in any multivibrator was increased by the injection of the control voltage into the common plate lead of the multivibrator tubes, as compared with injection into the circuits of either tube individually. Such increased stability is obtained, however, only if the multivibrator tube circuits are unsymmetrical so that an appreciable resultant plate current exists in the common lead.

The use of the unsymmetrical multivibrator in this connection resulted from earlier work by one of the authors with the symmetrical arrangements. Dissymmetry was first attained through the use of tubes of different type, having widely differing filament emissions. Later work showed the same result was obtained with tubes of the same type, if the circuit constants were made dissymmetrical, as by the use of resistances 20 to 50 times as great in one tube plate circuit as in the other.

As a result of this dissymmetry, one tube operates as a "throttle," the operating point sweeping across the entire characteristic from saturation to cut-off, while the other operates substantially as a normal amplifier. This type of operation, no matter how attained, is characteristically favorable for stable control.

A tube is employed between the controlling source and the multivibrator which does not function primarily as an amplifier, but as a one-way relay, whose purpose is to isolate the standard source from reactions due to the multivibrator. This is not only generally desirable, but it is a necessity if the standard is to maintain its frequency with extreme constancy. An ordinary vacuum-tube amplifier circuit is not sufficient when the controlling frequency is as high as 50 kc. Either a tetrode, utilized as a "screened grid" amplifier, or a carefully neutralized triode, must be employed.

In this work the choice of the standard was made in favor of a very heavy quartz bar whose frequency lay close to 50 kc. For convenience, only, the order of frequency division was taken as 50, so that the controlled multivibrator fundamental would be close to 1 kc. The impulse motor and clock train were designed to keep correct time when the frequency applied was 1,000 cycles per second, so that with this division the timing of the high-frequency source is reduced to observations of small time errors indicated by the clock.

The schematic circuit arrangement for a single controlled multivibrator is given in Fig. 1. In the absence of the tetrode and the resistance R, the uncontrolled multivibrator remains. In this work the resistances were fixed and variation of the fundamental frequency of the multivibrator attained by simultaneous variation of the capacities C. In the uncontrolled state, variation of these capacities produces a corresponding smooth variation of fundamental frequency of the multivibrator.

The application of a controlling voltage, e_c, to the grid of the isolating tube results in the injection of a voltage of the same frequency into the multivibrator circuit. Provided that the voltage is sufficiently great, that is, greater than a few hundredths of a volt, variation of the condensers C no longer produces a smooth and continuous change of fundamental frequency of the multivibrator. For certain separated ranges of values for C, the fundamental frequency of the multivibrator assumes discreet values, these being submultiples of the control frequency and invariant over the particular range of C. Between the ranges of C at which these discreet frequencies exist there are "transition" ranges in which no stable value exists for the fundamental frequency of the multivibrator. In these transition ranges the multivibrator attempts to oscillate in the controlled and uncontrolled states simultaneously, or, if the control voltage be
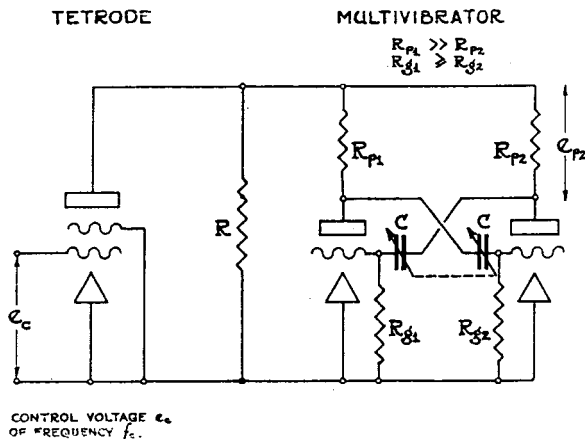

Fig. 1—Multivibrator of Fundamental Frequency f_c/n, where n is order number of harmonic at which control takes place.

sufficiently great, in adjacent controlled states. Observed by oscillograph, it is seen that in the latter case the fundamental oscillation of the multivibrator consists of a number of cycles of one discreet frequency and then one or more cycles at another discreet frequency. The oscillations alternate between the two frequencies in an irregular manner, there being no definite number of cycles in sequence of either of the two frequencies.

With small values of controlling voltage the operation is generally such that in the transition ranges of capacity, between those at which discreet and invariant values of fundamental frequency are obtained, the multivibrator oscillates in the uncontrolled condition. The regions in which control is attained

are well defined and the controlled state is fairly stable. This mode of operation may be termed the "under-voltaged controlled state." If the control voltage be increased in magnitude, the transition ranges of capacity over which uncontrolled or unstable operation is obtained, are reduced progressively as the control voltage magnitude is raised, until finally the multivibrator fundamental frequency changes abruptly from one mode to the next upon varying the capacities through a very small transition range. This state of control may be termed the "over-voltaged controlled state" and represents that condition of operation which is believed to be the most stable and most desirable. In this condition, variation of capacity from maximum to minimum results in the production of a series of discreet fundamental frequencies for the multivibrator, the number of such frequencies which may be obtained being dependent upon the range of variation of capacity and upon the order of control which has been set up.

If the control voltage be increased beyond the point at which the transition ranges first shrink substantially to zero an effect which may be termed "drawing" is produced. This drawing effect consists of a progressive increase in the multivibrator fundamental frequency through discreet steps representing the successive harmonic control orders, as the amplitude of the control voltage is increased. In other words, the fundamental frequency is drawn toward the control frequency as the control influence is made stronger. If a particular control order is desired this drawing effect must be compensated by an increase in the multivibrator capacity or resistance. But this in turn tends to move the time constant of the multivibrator circuit away from the fundamental frequency at which it is being forced to oscillate, which ultimately reduces the control stability on its own account. The net result of these effects is the appearance of a fairly definite *optimum value* of control voltage for any given harmonic order.

We come now to somewhat more generalized conclusions concerning the dependence of the control range, the control order and the wave-form of the multivibrator oscillations upon variations of control voltage magnitude, variations in multivibrator fundamental frequency as produced by *symmetrical* variations in the multivibrator circuit constants, and by variations in the *degree of dissymmetry* of the multivibrator circuit pro-

duced by a non-symmetrical variation of the circuit constants.
These considerations are best indicated by an outline:

1. {Variations in control voltage, e_c.
   - Small e_c — { Limited control range, though control is stable within range.
   - Waveform of same type for various orders of control.
   - Large e_c. — { Maximum control range; further increases of control voltage produce changes in order of control by "drawing," with narrowing of control range if e_c be made large enough.

2. {Variations in multivibrator fundamental frequency due to symmetrical changes in circuit constants. (C, C, varied).
   - { Control order changes in successive steps to lower orders as fundamental frequency of multivibrator is raised toward control frequency.
   - Control range narrow with small e_c; control range wide with large e_c.
   - Waveform of same type for the various contro orders.

3. {Variations in degree of dissymmetry of multivibrator circuit. (R_{p2} only varied)
   - { Control order remains constant.
   - Waveform alters in discreet steps to forms in which the "positive" and "negative" portions of the wave are in *integral ratios of time*, the total time remaining constant.

Based upon the experimental evidence, an important generalization may be drawn. *Symmetrical changes* in *circuit constants* produce effects similar to *symmetrical changes* in *control voltage magnitude*. (Changes in control voltage are inherently symmetrical in the arrangement used, since the same voltage is injected in the plate circuits of both tubes.) These effects are characterized by control at successive orders with no major changes in the waveform. Changes in the *degree of dissymmetry* of the circuit result in *discreet changes of waveform*, the control order usually remaining fixed. These changes of waveform are characterized by discreet changes in the ratio of time of "negative" to time of "positive" portion of cycle, the total time remaining constant.

It is worthy of note that under no operating condition was the stability of control improved by distorting the waveform of the control voltage to produce harmonics which might "lock in" with the higher harmonics of the multivibrator. This appears to be due to the fact that the effect which we term "control" occurs at a certain definite phase relation between the control wave and the corresponding multivibrator harmonic, and the phase differences between the higher harmonics of both sources, although invariant, may either aid or oppose the control which is already established.

The oscillograms of Fig. 2 indicate the phenomena observed. These oscillograms are line drawings of experimental observations of the plate current in that multivibrator tube which operates through the low external plate resistance. This current has in all cases the same general waveform as the relatively minute

plate current in the throttle tube and also the current in the
common plate circuit which includes the control tube.

Diagram A indicates the changes resulting from variations of
the magnitude of the control voltage, all other factors remaining
constant. The waveform remains essentially the same. As the
control voltage is raised, the fundamental frequency of the multi-
vibrator is also raised, being "drawn" toward the frequency of
the controlling voltage. These observations give a reasonable
explanation of the fact that in a symmetrical multivibrator a
strong preference is evidenced for control to take place at even
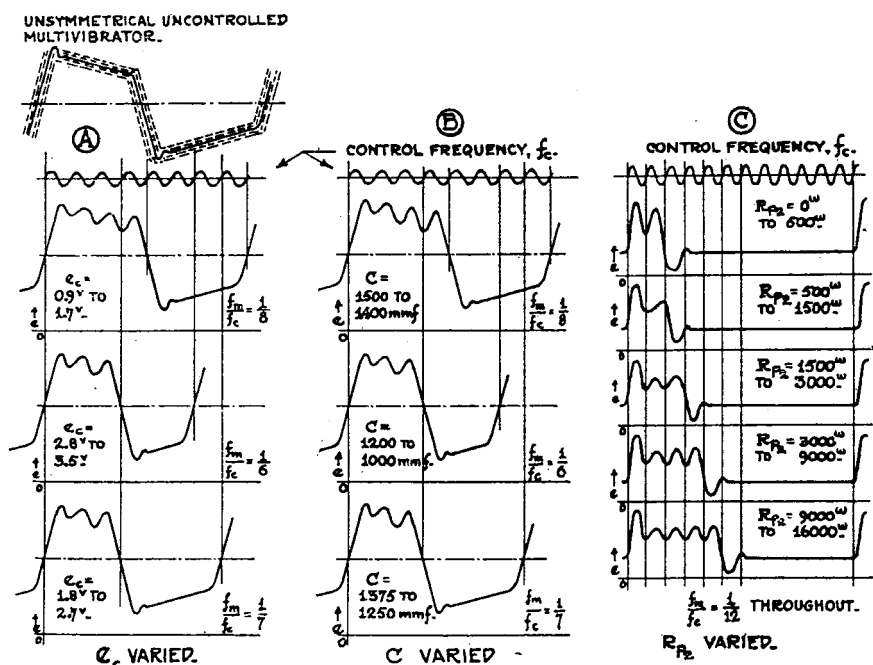ratios, because of the symmetry of the "positive" and "negative"

Fig. 2—Waveform and Frequency of Controlled Multivibrator, as shown by
e_{p2} (Fig. 1), as functions of e_c, Cm, and R_{p2} as variables.

portions of the wave. With the dissymmetrical multivibrator
such a preference does not appear to exist, which is explainable
on the basis that the inherently unsymmetrical waveform readily
adjusts itself so that one portion of the wave occupies a time
interval equal to that of an odd number of cycles of the con-
trolling frequency, while the other portion of the wave occupies
a time interval corresponding to an even number of cycles of the
control frequency. These conditions are illustrated in particular
by the lower diagram for the frequency ratio of 1/7. Here the
"positive" portion of the wave occupies a time interval of 3

cycles of the control frequency, while the "negative" portion occupies a time interval of 4 cycles. If the waveform is more nearly symmetrical, the multivibrator must be forced to operate dissymmetrically, by the controlling influence, in order that odd frequency ratios may be obtained, consequently requiring a greater controlling influence than in the unsymmetrical case.

In diagram B are shown sketches of the waveforms resulting from variation, in a symmetrical manner, of the capacities C of the multivibrator circuit, all other factors remaining constant. The waveform is seen to remain essentially constant but the frequency assumes three discreet values, bearing the ratios 1/6, 1/7, and 1/8 to the controlling frequency. The most stable adjustment of capacities is at a value slightly below the middle of the control range.

These two diagrams, 2A and 2B, illustrate clearly the equivalent effects of symmetrical changes of controlling voltage and of circuit constants upon the waveform and frequency of the multivibrator oscillations.

Diagram 2C indicates the changes in waveform as the lower of the two plate circuit resistances of the multivibrator is varied. In this case R_{p1} was 400,000 ohms, R_{p2} variable between 0 and 18,000 ohms, and R was 10,000 ohms. The multivibrator remained in control at all values of R_{p2}, with a fundamental frequency which was one-twelfth of the controlling frequency. The successive discreet waveforms were obtained over considerable ranges of values for R_{p2}, as indicated by the marginal notations in the figure. The integral ratios of the times for the two portions of the cycle are clearly indicated, as well as the manner in which the serrations due to the controlling frequency shift by single units as R_{p2} was continuously varied.

The assembly finally employed consists of two multivibrators in cascade, the choice of ratios being determined by the available standard frequency, the normal frequency of the clock motor and the fact that a series of harmonics based on 10-kc fundamental frequency was desired for calibration purposes. While frequency ratios with a single multivibrator of the order of 50 may be obtained with stable operation, it would have been necessary to utilize a second multivibrator in this case to obtain the desired harmonic series. Therefore the multivibrators were compounded, the first operating with a frequency ratio of 5, whose fundamental frequency was therefore 10 kc, and the second with a frequency

ratio of 10, whose fundamental was consequently 1 kc. Provision was made for a small coupling coil to be inserted in the first multivibrator circuits so that the series of 10-kc harmonics could be utilized external to the assembly. The complete wiring diagram of the assembly is given in Fig. 4, on which the values of the various circuit constants are shown as well as the normal ranges of supply voltages, through which stable control was obtained.

With careful adjustments of the condensers C, *within the control range*, stable operation has been attained for the following ranges of supply voltages, the frequency ratio being 50 for the entire assembly:

e_c from 1.8 to 2.8 volts, at 50 kc

E_f from 3.5 to 6.0 volts

E_p from 90 to 135 volts (or more)

While ranges of supply voltages such as given above have been attained many times, the ranges shown on the diagram are more indicative of nominal conditions, in which no excessive care has been used in making the adjustments. Under these conditions no difficulties are encountered in operation while "trickle charging" the filament and plate batteries from the commercial 60-cycle power line.

The foregoing observations indicate that by injecting a 50-kc voltage into the circuits of the compound multivibrator it is possible to establish a highly stable condition in which the fundamental and all the harmonics of both multivibrator elements are constant in frequency to the same degree that the injected voltage is constant. Moreover, the fundamental output at 1 kc bears every indication of being precisely controlled by the injected voltage. However, the exact mechanism of this control effect has not been analyzed, and we still have no direct experimental evidence that, when the multivibrator operates in a condition which has the physical characteristics of being "controlled," its fiftieth harmonic actually bears a constant phase relation to the control oscillation.

As a final critical test of this point, simultaneous observations of the control oscillation and the fundamental constituent of the multivibrator were made by means of a Braun tube. The circuit arrangement is indicated in Fig. 3A. Two tetrode amplifiers were used, one coupled loosely to the quartz oscillator furnishing

the control voltage, and the other to the ouptut of multivibrator *A* or multivibrator *B*. The output circuits of the amplifiers were carefully tuned so as to emphasize the fundamental frequencies of the standard oscillator and the multivibrator. When the circuits were not accurately resonant, the patterns indicated by the Braun tube were highly distorted. For the operation of the compound multivibrator, with a frequency ratio of 5 in the first and of 8 in the second, the pattern given by the Braun tube appeared as sketched in Fig. 3B.

The form of the pattern clearly indicated the frequency ratio of 40, remaining entirely stationary. As the tuned circuits were changed, the phase of one frequency component could be shifted with respect to the other, of course, but with the circuits
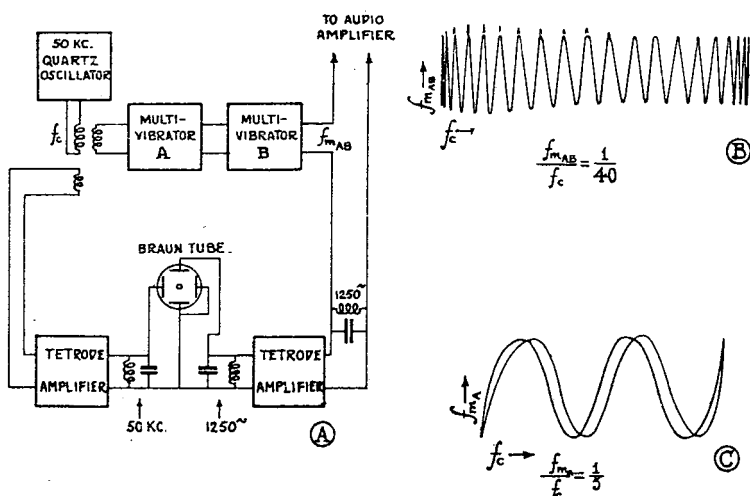

Fig. 3

fixed no visible fluctuations in frequency, phase, or amplitude took place. Upon changing either the resistances or the capacities of the multivibrator circuits, *keeping within the control range*, a change of phase was indicated by the pattern. This change of phase was "permanent,"—that is, varying the multivibrator constants displaced the phase and produced a new form of pattern, which form persisted until some further change was made.

A similar test, made between the frequency of the quartz oscillator and the output of the first multivibrator, gave a pattern which indicated the frequency ratio of 5, with no visible changes in phase or amplitude, indicated by Fig. 3C. As before, changing the multivibrator constants *within the control range* had the effect of changing the phase between the two voltages acting

on the Braun tube, but for fixed values of the constants the phase remained fixed over indefinite periods.   In both of these cases, variation of the circuit constants to a point where the control order changed indicated that a maximum phase variation of not more than 30 deg. (between the control wave and the synchronized harmonic of the multivibrator) could take place before the multivibrator jumped out of control at the desired order. In this test the multivibrator was brought to the edge of a transition range and the amplifiers were then adjusted to obtain the "in phase" pattern on the Braun tube screen. The multivibrator constants were then changed across the control range to the opposite transition point, the resulting change in phase being noted.

When in control, the controlling frequency may be varied by slight amounts, the multivibrator remaining in control. As the variation in frequency is made, the multivibrator suffers a slight phase displacement with respect to the standard frequency, but as long as the phase is not displaced beyond the limit of 30 deg., approximately, the phase takes up the new value and remains constant.

Continuous observations over periods of several hours have not indicated any perturbations of frequency, phase, or amplitude of sufficient duration to register on the Braun tube. After making the amplifier circuit adjustments necessary to obtain a distinctive pattern, on which any slight drift in phase would be readily observable, intermittent observations over periods of days have failed to show any change whatever in the phase of the synchronized multivibrator harmonic with respect to the control voltage.

We conclude from these observations that this state of oscillation of the multivibrator in the presence of a high-frequency injected oscillation which we have called the "controlled" oscillation throughout the discussion, is in fact an oscillatory state wherein the appropriate multivibrator harmonic bears a constant and permanent phase relation to the injected oscillation. Moreover, the frequency of this harmonic and hence of the fundamental follows any drift or perturbation in the frequency of the control oscillation without appreciably altering the phase relation or dropping out of synchronism even for a single cycle. The unsymmetrical multivibrator therefore constitutes a stable

submultiple generator suitable for converting the vibrations of the piezo oscillator into the rotation of a clock train.

4. The Piezo Oscillator

The circuit of the 50-kc piezo oscillator is shown in Fig. 4. The piezo element P is a normal-cut quartz bar, vibrating in the direction of its length; its approximate dimensions are 5.6 x 2.2 x 1.4 cm. Fig. 5 shows the complete assembly of the measuring equipment. On the lower shelf are the batteries and chargers. On the upper, left to right, are the 50-kc temperature-controlled crystal, crystal oscillator, first isolating amplifier, 10-kc multivibrator with coupling coil, second isolating amplifier, 1-kc multivibrator, 1-kc amplifier, and synchronous motor with clock train. The mounting is shown in Fig. 6. The bar is balanced on a metal support C having a felt wedge on its upper surface and confined between heavy metal condenser plates B by the screw E, carrying a felt pad, the whole assembly being mounted on a base of insulating material D. The holder and quartz bar are mounted in a constant-temperature chamber Q, Fig. 4. This constant-temperature unit consists of an aluminum casting of high heat capacity containing a cavity for the quartz condenser; the casting is surrounded by an insulating layer, which is in turn enclosed in a closed metal box R. Heat is supplied from coils distributed around this second metal box, the heating circuit being closed through a bimetallic thermostat positioned, with the heating coils, outside the second container. The whole is enclosed in a heavily insulated outer box of wood, W.

The quartz bar is maintained in oscillation by the triode T, operated from plate circuit batteries which are independent of the multivibrator batteries.

The quartz oscillator circuit is one of the general class in which sustained oscillations are impossible without the quartz bar. This type of circuit was chosen because experience with numbers of piezo oscillators used as secondary standards has indicated that the frequency of the oscillator is in general more precisely determined by the mechanical vibration of the quartz if no other periodic element is present which can support sustained oscillations independent of the mechanical vibrator. For this reason the regenerative element G, which is added to augment the regeneration through the grid-plate capacity of the triode, is a pure resistance. The load in the plate circuit, consisting of.

inductance L shunted by capacity C, is far removed from resonance at the frequency of the quartz bar. It merely represents a convenient method of obtaining the high inductive reactance required to sustain oscillations. The coil has an inductance of 20 mh and the capacity is normally set at about 0.0003 μf, thus providing an inductive reactance of approximately 15,000 ohms. This reactance is still approximately proportional to the frequency in the operating region. The capacity C was added, not to augment the voltage available from the oscillator, since an excess of amplification is provided in order to avoid the necessity of large amplitudes in the oscillator circuit, but merely to provide a means for making fine corrections on the oscillator frequency.
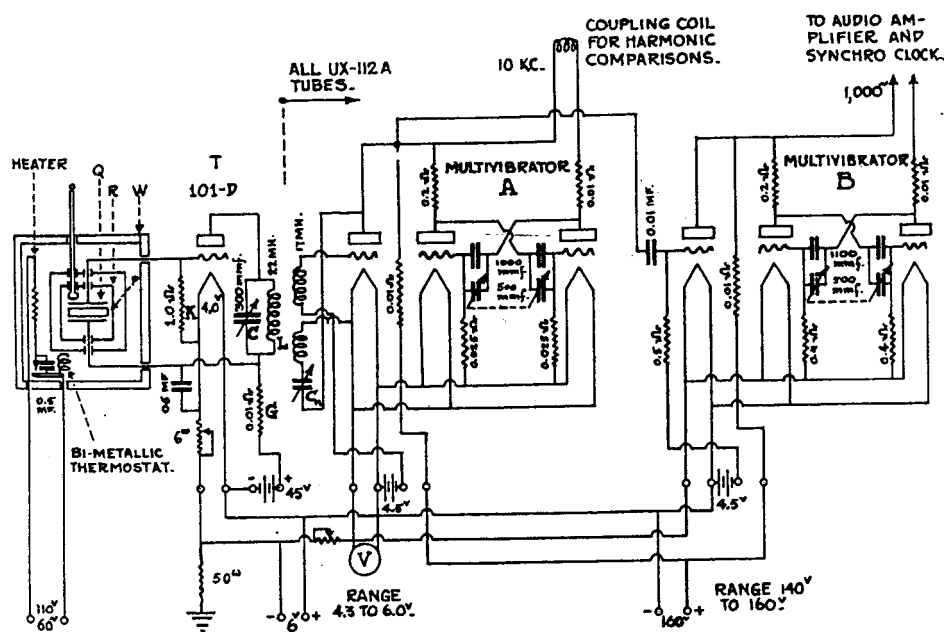

Fig. 4—Schematic Wiring Diagram of Controlled Compound Multivibrator.

The damping coefficient of the quartz bar itself has not been determined, but the characteristics of the whole oscillator in the actual operating region are as given in the following table. The figures here are the fractional change in frequency, positive or negative, for an increase of two per cent in the specified voltage or circuit element.

TWO PER CENT INCREASE IN:	FRACTIONAL CHANGE IN FREQUENCY
Plate Voltage	-0.02×10^{-6}
Filament Voltage	-0.04×10^{-6}
Resistance R_p	$+0.8 \times 10^{-6}$
Resistance R_g	-0.1×10^{-6}
Capacity	-3.0×10^{-6}

The temperature coefficient of the quartz bar and holder combined is -5.4×10^{-6} per deg. C.

5. Determination of an Unknown Frequency Between 500 and 1500 kc

The specific purpose of this development was to provide means for accurately adjusting a secondary standard oscillator to one of the even decimal frequencies between 500 and 1500 kc. These secondary standards are piezo oscillators including quartz plates mounted in holders with adjustable air gaps. The plates are adjusted to within one-tenth of one per cent by grinding, and the final setting is made by adjusting the air gap with a screw
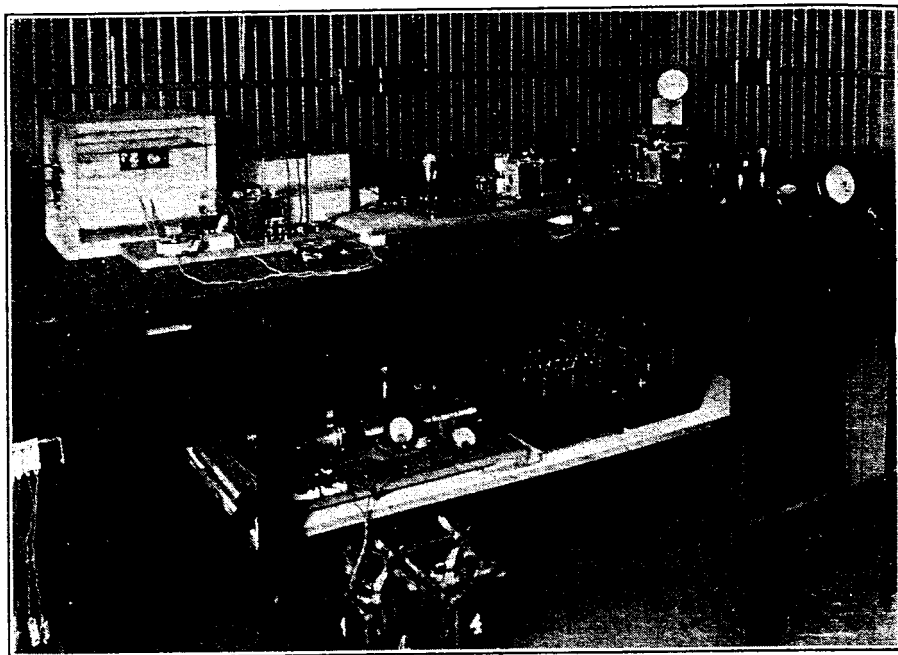

Fig. 5

provided for this purpose which is then locked. The process of referring the adjusted frequency to a standard time interval is carried out by coupling the oscillator under test loosely to the calibration coil of multivibrator A (see Fig. 4) which has a fundamental of 10 kc, then coupling a third oscillator and detector loosely to the combination, and listening with telephone receivers to the output of this detector as the oscillator under test is adjusted to beat zero with the appropriate harmonic of the multivibrator. This harmonic can be identified without difficulty with a subsidiary wavemeter, although there is usually not the

slightest ambiguity as to the order of the harmonic, since the preliminary adjustment of the test oscillator by grinding the quartz is carried out with the aid of a heterodyne wavemeter calibrated to an accuracy of 0.1 per cent and the beat note between the oscillator under test and the multivibrator harmonic is normally well within the audible range before final process is begun. Since a third frequency is superposed on the output of the multivibrator and the test oscillator, the frequency of the test oscillator can be adjusted aurally with a precision defined by about one beat in five seconds between it and the multivibrator.

When this adjustment has been made, the frequency of the oscillator under test is known directly in terms of the frequency of the quartz bar at the time of the measurement, and thus in terms of the standard time interval, to a precision which depends upon how closely the frequency of the quartz is maintained at its average value.
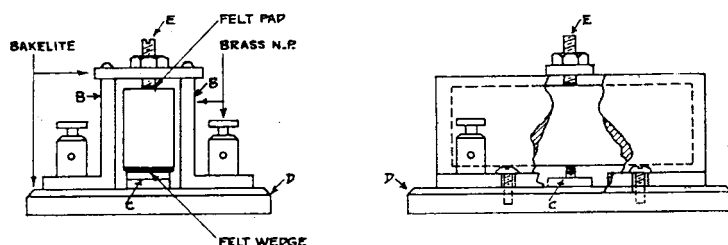

Fig. 6—Quartz Bar Mounting.

The standard time interval now employed in this work is one mean solar day, as indicated by radio time signals from the U. S. Naval Observatory. The oscillation counter consists of a small synchronous motor geared down through a clock train to a large second hand making one rotation per minute. The synchronous impulse motor has a toothed rotor of 120 teeth, and is driven by two U-shaped magnets around which the drive coils are wound. The gearing is such that the second hand indicates true solar time when the driving current has a fundamental frequency of 1 kc per second. The dial reading is compared visually with the standard time signals with a probable error of not over 0.05 second, the mean being derived from ten consecutive observations. Thus the mean frequency over each 24-hour interval is observed with a probable error slightly over one-half part in a million. The use of a longer standard time interval to reduce

the error in observing the mean frequency will not be justified until substantial reductions are made in the probable short-period perturbations from the mean frequency.

The fluctuation of the frequency during the first ten days in August, 1928, is shown graphically in Fig. 7. Each point in this curve indicates the average frequency during the preceding 24-hour interval except in two cases, where the interval was 48 hours. The horizontal line marked "Mean Frequency 50,007.6 cycles, per second" is the average for ten days. The maximum deviation from the 10-day mean is 0.36 cycle during the fourth and fifth days.

The limitations at present imposed upon the commercial standards to be calibrated require that they be adjusted to an accuracy of ten parts in one hundred thousand or better. The
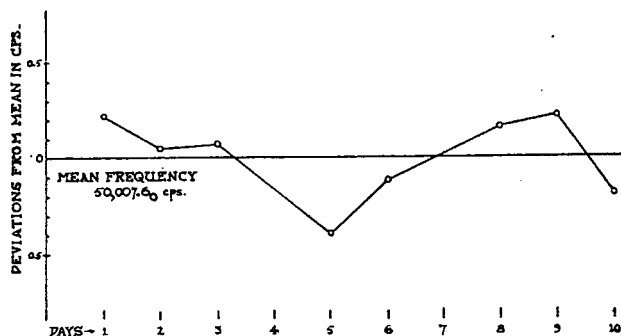

Fig. 7

24-hour mean frequency of the calibration oscillator is known to well within one part in one million. The battery voltages are held within such limits that the short-period fluctuations attributable to them are probably negligible compared with the fluctuations due to temperature. A definite correlation was observed between the temperature and the long-period fluctuations of Fig. 7. It is reasonable to assume that the momentary perturbations from the 24-hour mean are not greater than the maximum fluctuation from the mean observed in a long interval, which is of the order of eight parts in one million. Thus if the calibration is performed with a precision defined by 0.2 cycle in 500,000 or more, the normal accuracy at present attainable in adjusting the oscillator under test is about eight parts in one million which is safely within the current requirements. The piezo oscillator has recently been adjusted to a mean frequency of 50000.15 cycles per second, and in most oscillator calibrations the correction to 50

kc is neglected, allowing the adjustment to zero beat of the oscillator under test.

The variations in mean frequency of the piezo oscillator as indicated in Fig. 7, while insignificant as regards present requirements, are of course much too large for a precision standard, and are not representative of the possible performance of the system under the most favorable conditions which modern technique of temperature and circuit control may afford.

In an effort to improve the performance of the standard, a new temperature control box was built, though use was still made of the bimetallic thermo-regulator. The fluctuation of the frequency during the ten-day interval from November 4, 1928, is shown graphically in Fig. 8. The improvement over the performance shown by Fig. 6 is apparent, but the results still leave
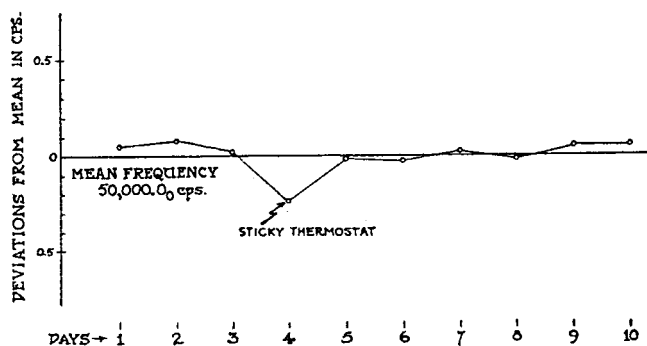

Fig. 8

room for considerable effort. Outstanding lines of development to be pursued are (1) provision of temperature control within one or two hundredths of a degree; (2) replacement of present insulation in the quartz-bar holder by a vitreous material showing negligible distortion with age at constant temperature; (3) improvements in the clock mechanism and in methods of checking against the time signals to provide a higher degree of accuracy in measuring the time interval.

ADDITIONAL BIBLIOGRAPHY

M. Mercier, "Sur la Synchronisation Harmonique des Oscillators Electriques," *Comptes Rendus*, **174**, 448, 1922.

H. Abraham and E. Bloch, "Mesure en Valeur Absolue des periods des Oscillations Electriques de Haute Frequence," *Ann. de Physique*, **12**, 237, 1919.

Balth van der Pol, Jr., "Frequency Demultiplication," *Nature*, Sept. 10 1927.